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Translational Velocities and Rotational Rates of Interstellar Dust Grains

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Abstract.
Interstellar dust grains exhibit complex dynamics which is essential for understanding many key interstellar processes that involve dust, including grain alignment, grain growth, grain shattering etc. Grain rotational and translational motions are affected not only by gaseous collisions, but also by interactions with ions, photons, magnetic fields etc. Some of those interactions, e.g. interactions of ions with the dipole electric moment of dust grains, require the quantum nature of the process to be accounted for. Similarly, coupling of rotational and vibrational degrees of freedom in a grain happens due to relaxation processes, among which the process related to nuclear spins frequently is the dominant one. This coupling modifies substantially both the dynamics of rotational and translational motions by inducing grain flips. The flipping averages our certain systematic torques and forces that act on grains. As the rate of flipping is larger for smaller grains, these grains can be "thermally trapped", i.e. rotate at a thermal rate in spite of the presence of systematic torques. Moreover, a subset of small grains with high dipole moments may rotate at subthermal rates due to high damping arising from grain emission in microwave range of frequencies. Translational and rotational dynamics of grains is interrelated. For instance, both rotation and gas grain relative speeds affect grain alignment as well as determine grain size distribution and structure. Translational dynamics of grains is mostly dominated by grain interactions with magnetohydrodynamic turbulence. Efficient turbulent mixing of dust grains limits the degree to which grains of different sizes may be segregated in space.

1. Why do we care?

Dust is an important constituent of the interstellar medium (ISM). It interferes with observations in the optical range, but provides an insight to star-formation activity through far-infrared radiation. As dust gets aligned in the external magnetic field (Hall 1949; Hiltner 1949) it traces the magnetic field via emission and extinction polarization (see reviews by Hildebrand et al. 2000; Lazarian 2003). Grain alignment is a property of rotating grains. Fast rotation makes grains less susceptible to disorientation by collisions with gas atoms, but it also limits the efficiency of some alignment mechanisms. In addition, fast rotating grains are the sources of microwave emission that interferes with measurements

of Cosmic Microwave Background (CMB) intensity and polarization (Draine & Lazarian 1998a; see also recent review by Lazarian & Finkbeiner 2003).

The basic properties of dust (optical extinction, dust chemistry, heating of the ISM etc) strongly depend on its size distribution (Biermann & Harwit 1980; O'donnell & Mathis 1997). The latter evolves As a result of grain collisions, whose frequency and consequences depend on grain relative velocities (Draine 1985).

Rotational and translational motions are not independent. For instance, the difference in the number of active sites of H_2 formation over the parts of the grain perpendicular to the axis of grain rotation can result in uncompensated force accelerating the grain (Purcell 1979, Lazarian & Yan 2002, henceforth LY02). However, if a grain is undergoing frequent flips due to thermal fluctuations (Lazarian & Draine 1999a, henceforth LD99a and §2) the thrust will change direction and be averaged out. On the other hand, grain alignment presents a case when translational motion affects grain rotation. For instance, mechanical alignment of grains (see Lazarian 2003 and references therein) induces higher rotational rates if grains rotate thermally initially.

Damping of rotational and translational motions have many similarities. For instance, the interaction of grains having dipole moments with passing ions is important for damping of both types of motions. For the case of damping of translational motion the treatment of the process is given in Yan, Lazarian & Draine (2003, henceforth YLD03). Quantum cut-off discussed in §4 is applicable to this case as well.

In what follows we discuss how dust grains rotate (§2), at what rate they rotate (§3), and whether quantum effects are important for grain rotation (§4). We describe the translational motion of grains in §5. In §6 we discuss astrophysical implications of grain dynamics and provide the summary in §7.

2. Do grains rotate about their axis of major inertia?

Originally this question was asked in relation with the theory of grain alignment (see Fig. 1a and discussion in Lazarian 2003). To produce the observed starlight polarization, grains must be aligned with their long axes perpendicular to magnetic field. This involves alignment not only of grain angular momentum $\mathbf{J}$ in respect to the external magnetic field $\mathbf{B}$, but also the alignment of grain long axes in respect to $\mathbf{J}$. Jones & Spitzer (1967) assumed a Maxwellian distribution of angular momentum which favored the preferential alignment of $\mathbf{J}$ with the axis of the maximal moment of inertia (henceforth axis of major inertia). Purcell (1979, henceforth P79) later considered grains rotating much faster than the thermal velocities (see §3) and showed internal dissipation of energy in a grain will make grains rotate about the axis of major inertia.

Arguments in P79 can be easily understood. Indeed, for an oblate grain (see Fig. 1b) with angular momentum J the energy can be written as

$$E(\theta) = \frac{J^2}{I_{max}}\left(1 + \sin^2\beta(h-1)\right) \quad , \tag{1}$$

where $h = I_{max}/I_{\perp}$ is the ratio of the maximal to minimal moments of grain inertia. Internal forces cannot change the angular momentum, but it is evident

from eq.(1) that the energy can be decreased by aligning the axis of maximal inertia along **J**, i.e. by decreasing β. P79 discussed two possible causes of internal dissipation, the first one related to the well known inelastic relaxation (see also Lazarian & Efroimsky 1999), the second is due to the mechanism that he discovered and termed "Barnett relaxation".

We remind the reader that the Barnett effect is converse of the Einstein-de Haas effect. If in Einstein-de Haas effect a paramagnetic body starts rotating during remagnetizations as its flipping electrons transfer the angular momentum (associated with their spins) to the lattice, in the Barnett effect the rotating body shares its angular momentum with the electron subsystem causing magnetization. The magnetization is directed along the grain angular velocity and the value of the Barnett-induced magnetic moment is $\mu \approx 10^{-19}\omega_{(5)}$ erg gauss^{-1} (where $\omega_{(5)} \equiv \omega(\mathrm{s}^{-1})/10^5$)[1].

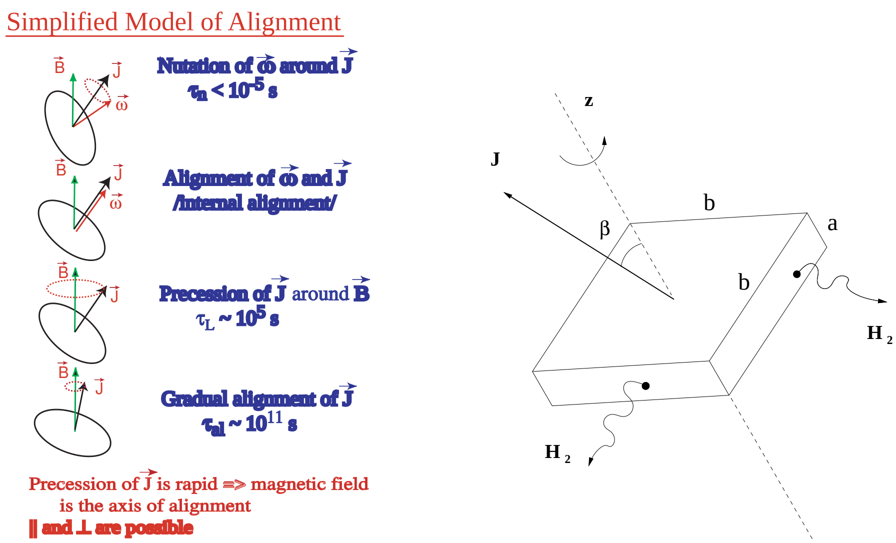

Figure 1. *Left panel*– Grain alignment implies several alignment processes acting simultaneously and spanning many time scales (shown for 10^{-5} cm grain in cold interstellar gas). The rotational dynamics of a grain is rather complex. The internal alignment introduced by Purcell (1979) was thought to be slower than precession until Lazarian & Draine (1999b, henceforth LD99b) showed that it happens 10^6 times faster when relaxation through induced by nuclear spins is accounted for (approximately 10^4 s for the 10^{-5} cm grains). *Right panel*– Grain rotation arising from systematic torques arising from H_2 formation (P79). In the presence of efficient internal relaxation the angle β between the axis of maximal moment of inertia and **J** is small is grain is rotating at suprathermal rates ($E_{kinetic} \gg kT_{grain}$).

[1]Therefore the Larmor precession has a period $\tau_L \approx 3\times10^6 B_{(5)}^{-1}$ s (where B_5^{-1}) and the magnetic field defines the axis of alignment (see more details in Lazarian 2003)

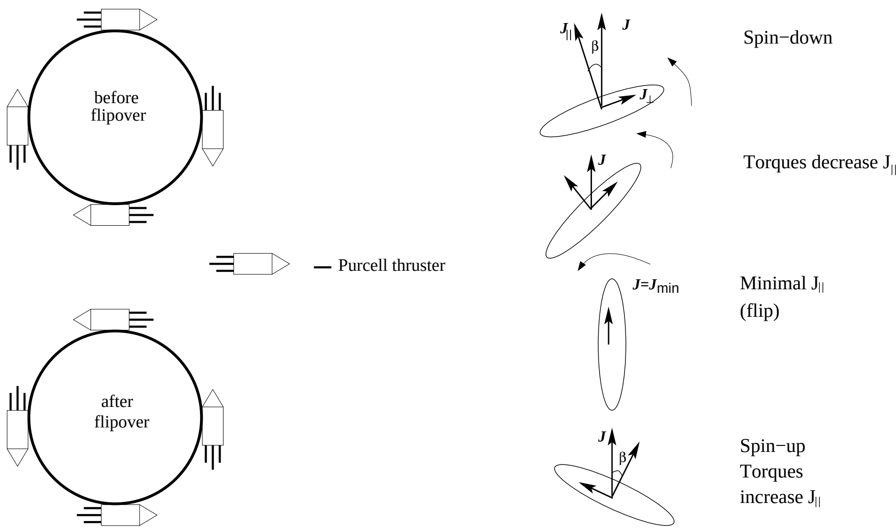

Figure 2. *Left panel*– Schematic of a grain affected by Purcell's torques before and after a flipover event. As the grain flips the direction of torques changes. H_2 formation sites act as thrusters in the figure. *Right panel*– Regular crossover event as it described by Spitzer & McGlynn (1979). The systematic torques decrease the amplitude of **J** component parallel to the axis of maximal inertia to zero while preserving the other component, $J_{\perp}$. If $J_{\perp}$ is small then the grain is susceptible to randomization during crossovers. The direction of **J** is preserved in the absence of random bombardment.

The Barnett relaxation process may be easily understood. We know that a freely rotating grain preserves the direction of **J**, while angular velocity precesses about **J** and in grain body axes. The "Barnett equivalent magnetic field", i.e. the equivalent external magnetic field that would cause the same magnetization of the grain material, is $H_{BE} = 5.6 \times 10^{-3}\omega_{(5)}$ G. Due to the precession of angular velocity the "Barnett equivalent magnetic field" changes in grain axes. This causes remagnetization accompanied by the inevitable dissipation. As a result $E(\theta)$ and therefore θ decreases.

The Barnett relaxation happens on the scale $t_{Bar} \approx 4 \times 10^7 \omega_{(5)}^{-2}$ sec, very short compared to the time t_{gas} over which randomization through gas-grain collisions takes place. As a result, models of interstellar polarization developed since 1979 have often assumed that Barnett dissipation aligns **J** *perfectly* with the major axis of inertia. However, Lazarian (1994, henceforth L94) has pointed out that this is a poor approximation if the grains rotate with thermal kinetic energies: thermal fluctuations in the Barnett magnetization will excite rotation about all 3 of the body axes, preventing perfect alignment unless the rotation is suprathermal or the grain solid temperature is zero. The exact analysis of the problem was given in Lazarian & Roberge (1997), where the distribution of θ for a freely rotating grain was defined through the Boltzmann distribution $\exp(-E(\theta)/kT_{grain})$, where T_{grain} is the grain temperature.

3. How fast do the grains rotate?

Earlier work in the field assumed Brownian grain rotation with the effective temperature equal to the mean of the grain and gas temperatures (see Jones & Spitzer 1967). The complexity of grain rotation was realized only later. Purcell (1975; 1979) realized that grains may rotate at a much faster rate resulting from systematic torques. P79 identified three separate systematic torque mechanisms: inelastic scattering of impinging atoms when gas and grain temperatures differ, photoelectric emission, and H_2 formation on grain surfaces (see Fig. 1b); we will refer to these below as "Purcell's torques". The latter was shown to dominate the other two for typical conditions in the diffuse ISM (P79). The existence of systematic H_2 torques is expected due to the random distribution over the grain surface of catalytic sites of H_2 formation, since each active site acts as a minute thruster emitting newly-formed H_2 molecules.

Independent of Purcell, Dolginov (1972) and Dolginov & Mytrophanov (1975) identified radiative torques as the way of spinning up a subset of interstellar grains. "Helical" grains would scatter differently left and right polarized light and therefore ordinary unpolarized light would spun them up. This subset of "helical" grains was believed to be somewhat limited to special shapes/materials. This work did not make much impact to the field until Draine & Weingartner (1996) showed that grains of arbitrary irregular shapes get spun up when their size is of the order of the starlight wavelength.

The arguments of P79 in favor of suprathermal rotation were so clear and compelling that other researchers were immediately convinced that interstellar grains in diffuse clouds should rotate suprathermally. Purcell's discovery was of immense importance for grain alignment. Suprathermally rotating grains remain subject to gradual alignment by paramagnetic dissipation (Davis & Greenstein 1951), but due to their large angular momentum are essentially immune to disalignment by collisions with gas atoms.

Spitzer & McGlynn (1979, henceforth SM79) showed that suprathermally rotating grains should be susceptible to disalignment only during short intervals of slow rotation that they called "crossovers" (see Fig 2, right). During a crossover the grain slows down, flips and is accelerated again. Crossovers are due to various grain surface processes that change the direction (in body-coordinates) of the systematic torques. Therefore for sufficiently infrequent crossovers suprathermally rotating grains will be well aligned with the degree of alignment determined by the time between crossovers, the degree of correlation of the direction of grain angular momentum before and after a crossover (SM79), and environmental conditions (e.g., magnetic field strength B).

The original calculations of SM79 obtained only marginal correlation of angular momentum before and after a crossover, but their analysis disregarded thermal fluctuations within the grain material. Indeed, if the alignment of $\mathbf{J}$ with the axis of major inertia is perfect all the time through the crossover the absolute value of $|\mathbf{J}|$ passes through zero during the crossover. Therefore gas collisions and recoils from nascent H_2 molecules would *completely* randomize the initial and final directions of $\mathbf{J}$ during the crossover. Thermal fluctuations partially decouple $\mathbf{J}$ and the axis of major inertia (see §2). As a result the minimal value of $|\mathbf{J}|$ during a crossover is equal to the component of $\mathbf{J}$ perpendicular to the

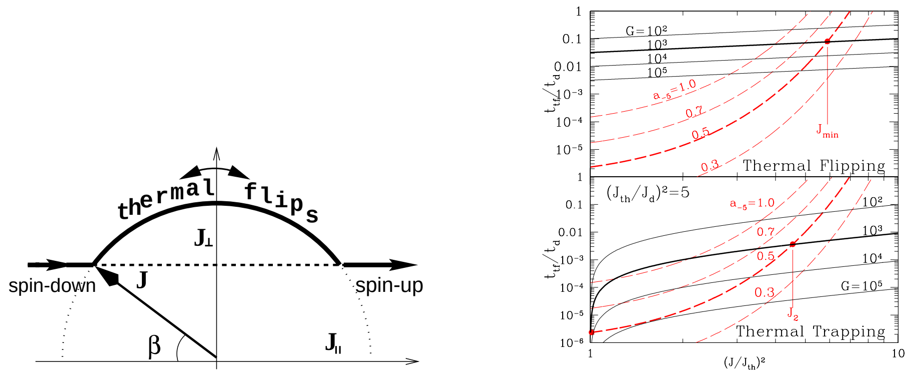

Figure 3. *Left panel*– Grain trajectory on the $J_\perp - J_\parallel$ plane, where $J_\perp$ and $J_\parallel$ are components of $\mathbf{J}$ perpendicular or parallel to the grain's principal axis of largest moment of inertia. The solid trajectory shows a "thermal flip", while the broken line shows the "regular" crossover which would occur in the absence of a thermal flip. From LD99a. *Right panel*– Top: Thermal flipping to damping ratio as a function of $J/J_{thermal}$ for grains of given size [broken lines, labeled by $a_{-5} \equiv a(cm)/10^{-5}$] and for grains with a given value of systematic torques [solid lines, labeled by G]. Dot shows $J_{\min} = \dot{J} \cdot t_{tf}$ for flipping-assisted crossover of $a_{-5} = 0.5$ grain with $G = 10^3$. Bottom: Thermal trapping for grains of given size [broken lines, labeled by a_{-5}], and given value of torques [solid lines, labeled by G]. From LD99a.

axis of major inertia. This value is approximately $J_{thermal} \sim (2kT_{grain}I_{max})^{1/2}$ and the randomization during a crossover decreases (Lazarian & Draine 1997, henceforth LD97). LD97 obtained a high degree of correlation of angular momentum direction before and after the crossover for grains larger than a critical radius $a_c \approx 1.5 \times 10^{-5}$cm, the radius for which the time for internal dissipation of rotational kinetic energy is equal to the duration of a crossover.

What would happen for grains that are smaller than a_c? Lazarian & Draine (1999a, henceforth LD99a) showed that instead of following the phase space trajectory prescribed by SM79 theory along which $J_\perp$ is approximately constant, while the component of $\mathbf{J}$ parallel to the axis of maximal inertia $J_\parallel$ changes sign, the grains undergo flipovers (see Fig2a) during which $|J|$ does not change (see Fig3a). If these flipovers repeat; grains get "thermally trapped" (LD99a and Fig3b). This process can be understood in the following way. For sufficiently small $|J|$ the rate of flipping t_{tf}^{-1} becomes large. Purcell's torques change sign as grain flips. As a result, grain J^2 undergoes a random walk over the time of grain rotational damping t_d. If J_{th} is the momentum of a thermally rotating grain, the expected value of the mean squared angular momentum $\langle J^2 \rangle$ will be approximately $J_{th}^2 + (G-1)J_{th}^2 t_{tf}/(t_d + t_{tf})$, where G is defined by the systematic Purcell's torque being $(G-1)^{1/2} J_{th}/t_d$. As $t_{tf}(J^2)$ is a non-linear function of angular momentum the solution for the angular momentum is bistable. For sufficiently small initial J^2 less than the critical value J_{cr}^2, it tends to $\approx J_{th}^2$, while for of $J^2 > J_{cr}^2$ it tends to its suprathermal value predicted by Purcell

i.e. $\approx GJ_{th}^2$. A suprathermally rotating grain has chances to become thermally trapped and stay in the trapped state for $\approx t_d \exp[(J_{cr}/J_{th})^2]$ till fluctuations in the value of the angular momentum rescue the grain from the trap. As a result a substantial part of grains smaller than a_{cr} will not rotate at high rates predicted by P79 even in spite of the presence of systematic torques that are fixed in body coordinates. Thermally rotating grains are subject to randomization by gaseous collisions and are marginally aligned for typical interstellar fields (see Lazarian 1997a; Roberge & Lazarian 1999). Other consequences of thermal trapping and the values of a_{cr} that follow from processes different from the Barnett relaxation are discussed below. The LD99a model gives plausible predictions, but a more comprehensive quantitative study is necessary. We are aware of such a study being done by Roberge & Ford (in preparation; see also the contribution by Roberge (2004) to this volume).

Thermal trapping limits the range of grain sizes which can be spun up by Purcell's torques. One may expect that radiative torques are not much influenced by thermal trapping as they are not fixed in the grain axes and may not alter their direction due to grain flipping. A quantitative study by Draine & Weingartner (1996) shows that for typical interstellar spectra grains with sizes larger than 5×10^{-6} cm can be spun up by radiative torques[2] This means that in ISM grains larger than 5×10^{-6} cm rotate suprathermally[3], while small grains may rotate thermally.

Can grains rotate subthermally, i.e. with velocities which are substantially smaller than those of Brownian rotation? The answer to this is positive. Draine & Lazarian (1998a, henceforth DL98) showed that grains with sizes less than 10^{-7} cm may be efficient emitters of microwave radiation provided that they have dipole moments. The emission from those grains can account for the so-called Foreground X (De Oliveira-Costa et al. 2002) observed in the range 10-100 GHz (see Fig. 4a). The back-reaction from radiation slows down grain rotation. As a result, detailed calculations in DL98 showed that emitting grains may rotate at substantially subthermal velocities, resulting in considerably less microwave emission than had been estimated by Ferrara & Dettmar (1994), who assumed Brownian rotation.

4. Are quantum effects important for grain dynamics?

Dust grains are essentially macroscopic bodies. The rotational quantum number $J/\hbar > 100$ even for the smallest grains (DL98). Therefore the initial reaction is that grain dynamics can always be described using classical physics. This is not true, however.

DL98 showed that to describe the interaction of a grain with a dipole moment with ions one must account for the quantum nature of the interaction. Indeed, the pioneering work by Anderson & Watson (1993) assumed that ions within the Debye screening length interact with the grain dipole moment.

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[2] In the vicinity of stars with UV excess smaller grains can be spun up as well.

[3] An important point here is that radiative torques may not be dominant in terms of their absolute value, but still they can rescue grains from thermal trapping.

Calculations in DL98 showed that the more severe limitations on which ions can interact with grain dipole moment come in case of sufficiently small grains from the requirement that the angular momentum transfered in an individual[4] interaction should be multiples of $\hbar$.

Another case when quantum mechanics is important is related to the Barnett effect. The Barnett effect is a quantum effect, as it involves orientation of electron spins, which are quantum objects. P79 noted that an analog of the Barnett effect exists for nuclear spins. If a rotating body has initially an equal number of nuclear spins directed parallel and anti-parallel to the angular velocity $\vec{\Omega}$, it can decrease its kinetic energy, at constant total angular momentum $\mathbf{J}$, if some of the angular momentum is transfered to the nuclear spin system. Increasing the projection of the nuclear angular momentum along $\mathbf{J}$ by $+\hbar$ (at constant J) reduces the rotational kinetic energy by $\hbar\Omega$. If the rotating body is allowed to come into thermal equilibrium (without exchanging angular momentum) with a heat reservoir of temperature $T_{\rm dust}$ then particles of spin S develop a net alignment per particle

$$\frac{\sum_{m=-S}^{S} m \exp(m\hbar\Omega/kT_{\rm dust})}{\sum_{m=-S}^{S} \exp(m\hbar\Omega/kT_{\rm dust})} \ . \tag{2}$$

Note that this does not depend on the magnetic moment μ.

As the number of parallel and antiparallel spins becomes different the body develops magnetization. The relation between Ω and the strength of the "Barnett-equivalent" magnetic field $H_{\rm BE}^{(\rm n)}$ (P79) that would cause the same nuclear magnetization (in a nonrotating body) is given by

$$\mathbf{H}_{\rm BE}^{(\rm n)} = \frac{\hbar}{g_{\rm n}\mu_{\rm N}}\vec{\Omega} \quad , \tag{3}$$

where $g_{\rm n}$ is the so-called nuclear g-factor (see Morrish 1980), and $\mu_{\rm N} \equiv e\hbar/2m_{\rm p}c$ is the nuclear magneton, smaller than the Bohr magneton by the electron to proton mass ratio, $m_{\rm e}/m_{\rm p}$. A striking feature of eq. (3) is that the Barnett-equivalent magnetic field is inversely proportional to the species magnetic moment. As grain tumbles the magnetization changes in grain body coordinates and this causes paramagnetic relaxation. This relaxation is proportional to $\chi_N''(\omega)H_{BE}^2$ (where χ_N'' is the imaginary part of the nuclear contribution to the susceptibility) and is approximately 10^6 times faster for nuclear moments than for their electron counterparts[5].

The first striking question is why an effect so feeble as nuclear magnetism can be so important in terms of internal relaxation. The answer is that spins

[4]Excitation of plasma waves as an additional source of damping was considered in Ragot (2002). However, it is possible to show that for small interstellar grains considered in DL98 collective plasma effects are negligible.

[5]Obviously enough this sort of arguments fails when the rate of rotation is larger than the rate at which nuclear spins interact. The latter depends on the concentration of nuclear spins. For the ISM dust LD99b concluded that the nuclear relaxation is dominant for thermally rotating grains larger than $\sim 5\times10^{-6}$ cm.

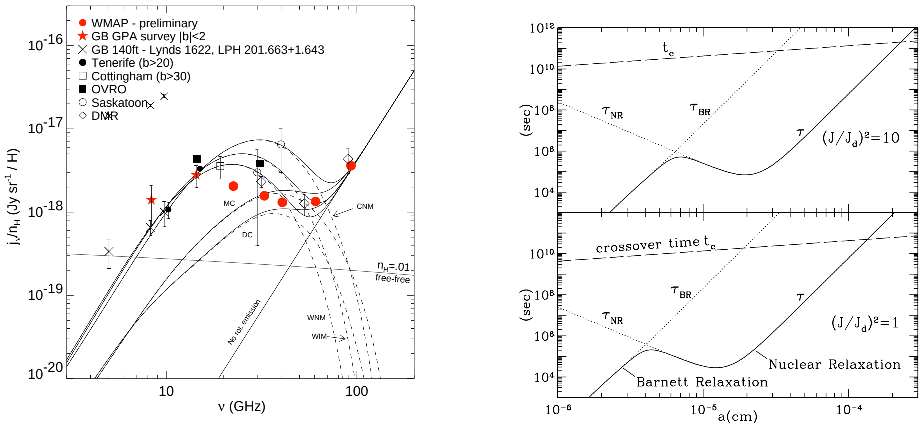

Figure 4. *Left panel*– Emission of spinning grains for different phases of interstellar media in the model by Draine & Lazarian (1998b) against observational data (WMAP data is by D. Finkbeiner). From Lazarian & Finkbeiner 2003. *Right panel* – Time τ for alignment of $\hat{a}$ with $\mathbf{J}$ for a freely rotating grain, due to dissipation associated with nuclear spins (nuclear relaxation) and electron spins (Barnett effect). Results are shown for grains with $(J/J_d)^2 = 1$ (bottom) and 10 (top). Also shown is the "crossover time" $t_c = J/\dot{J}_{\|}$, where the torque $\dot{J}_{\|}$ is due to H_2 formation with a density of active sites $10^{13}\mathrm{cm}^{-2}\mathrm{cm}^{-2}$ (From LD99b).

align in a rotating body because of their angular momentum, not because of their magnetic moments. The magnetic moment enters only as a means for the spins to exchange angular momentum with the lattice. The coupling within the electron spin system is very effective, with the result that there is minimal "lag" in the electron spin alignment when the grain angular velocity $\vec{\Omega}$ changes in grain body coordinates. In the case of the nuclear spin system, however, the value of the nuclear magnetic moment is large enough to provide significant coupling, but weak enough so that there is a significant lag[6] in the nuclear spin alignment when $\vec{\Omega}$ precesses around the grain axis of maximal inertia: the coupling is "just right" for nuclear relaxation to be extremely effective for $10^{-5}\mathrm{cm} \lesssim a \lesssim 10^{-4}\mathrm{cm}$ grains. The efficiency of nuclear relaxation drops for sufficiently high frequencies and therefore Barnett relaxation dominates for $a \lesssim 5 \times 10^{-6}\mathrm{cm}$, as seen in Fig. (4a).

As we discussed in §3, LD99a found that "thermal flipping" was an important element of grain dynamics for sufficiently small grains. LD99b have shown that internal relaxation associated with nuclear spin alignment can be many orders of magnitude more rapid than due to the Barnett effect for $a \gtrsim 10^{-5}\mathrm{cm}$ grains. As a result, the phenomena of thermal flipping and thermal trapping become important for grains as large as $\sim 10^{-4}\mathrm{cm}$.

[6]Purcell (1969) was the first to notice that for thermally rotating 10^{-5} cm grains the rate of paramagnetic alignment in the external magnetic field does not depend on the value of magnetic moment of the paramagnetic species. Therefore he concluded that the alignment of grains by interstellar magnetic field may happen due to nuclear spins only.

The Barnett effect is related to yet another quantum process relevant to the paramagnetic alignment of ultra-small grains ($< 10^{-7}$ cm) that is discussed in Lazarian & Draine (2000). Those grains produce important CMB foreground (see Fig. 4) which can be polarized if the grains are aligned.

Introduced by Davis & Greenstein (1951) paramagnetic relaxation is easy to understand: for a spinning grain the component of interstellar magnetic field perpendicular to the grain angular velocity varies in grain coordinate. The resulting time-dependent magnetization has associated energy dissipation and torques that damp grain rotation perpendicular to magnetic field.

Rotation removes the spin degeneracy of the electron energy levels. The energy difference between electron spin parallel or antiparallel to $\vec{\Omega}$ provides a level splitting corresponding to $\hbar\omega = g\mu_{\rm B}H_{\rm BE}$.

Now consider a (weak) static magnetic field $\mathbf{H}$ at an angle θ to $\vec{\Omega}$. In grain coordinates, this appears like a static field $H\cos\theta$ plus a field $H\sin\theta$ rotating with frequency ω. This rotating field can be resonantly absorbed, since the energy level splitting is exactly $\hbar\omega$.

This energy absorption, of course, is proportional to paramagnetic susceptibility $\chi''(\omega)$. In the classical Davis-Greenstein analysis this magnetic susceptibility $\chi(\omega)$ is taken to be that of a sample at rest in zero magnetic field: $\chi \equiv \chi(H_0 = 0, \omega)$. Here we point out that one should instead use $\chi = \chi_\perp(H_0 = H_{\rm BE}, \omega)$, where $\chi_\perp(H_0, \omega)$ describes the response of nonrotating material to a weak field rotating at frequency ω perpendicular to a static magnetic field H_0. Compared to classical Davis-Greenstein relaxation the study by Lazarian & Draine (2000) predicts that the relaxation happens at the maximal possible or resonance rate. Therefore the relaxation was termed "resonance relaxation". For grains of the order of 10^{-5} cm this results in a correction factor of order unity. For ultra-small grains it provides an enhancement of many orders of magnitude.

5. Is turbulence important for driving grains?

Depending on grain relative velocities, grain-grain collisions can have various outcomes, e.g., coagulation, cratering, shattering, vaporization and erosion and ejection of mantle material (see Draine 1985 and references therein). It is likely that some features of grain size distribution (Mathis, Rumpl & Nordsieck 1977; Kim, Martin & Hendry 1994), eg., cutoff at large size, are the result of fragmentation.

Dust dynamics is also influential to the metallicity in various astrophysical environment. The depletion of heavy elements in interstellar medium is a long puzzling problem. Grains moving supersonically may efficiently accrete gas-phase heavy elements (Weingartner & Draine 1999, Wakker & Mathis 2000). Dust ejection from galaxies is important to metal enrichment of intergalactic medium (see Aguirre et al. 2001 and references therein).

Various processes can affect the velocities of dust grains. Shocks, radiation, ambipolar diffusion, and gravitational sedimentation all can bring about a dispersion in grain velocities (Draine 1985).

Shock acceleration. The basic idea is that the weakly charged grains are like ions with high mass to charge ratio (Epstein 1980). Thus they can easily diffuse farther back upstream of the shock and be accelerated more efficiently to

suprathermal energies. Nevertheless, the shock acceleration is inefficient for low speed grains. The reason is that the efficiency of the shock acceleration depends on the scattering rate, which is determined by the stochastic interaction with turbulence. For low speed particles, the scattering rate is lower than the rate of momentum diffusion. In this case the stochastic acceleration by turbulence happens faster than dust acceleration by shocks (Park & Petrosian 1996, Yan & Lazarian 2003, henceforth YL03, see also below).

Effects of radiation fields. Grains are exposed to various forces in anisotropic radiation fields. Apart from radiation pressure, grains are subjected to forces due to the asymmetric photon-stimulated ejection of particles. A detailed discussion can be found in Weingartner & Draine (2001a, henceforth WD01; also the review by Draine 2003). The photoelectric force depends on the ambient conditions relevant to grain charging (WD01; Lafon 1990; Kerker & Wang 1982). The calculation by WD01 demonstrated that it is comparable to radiation pressure when the grain potential is low and the radiation spectrum is hard. Photodesorption is also a photon-stimulated ejection process, but of absorbed atoms on grain surface. However, because the surface physics and chemistry of grain materials are unclear, the calculation of the photondesorption force is highly uncertain (WD01). The bottom line is that the force due to photodesorption is expected to be comparable to the radiation pressure and photoelectric thrust (Draine 2003).

Motions arising from H_2 thrust. A different residual imbalance arises from the difference of the number of catalytic active sites for H_2 formation on opposite grain surfaces. The nascent H_2 molecules leave the active sites with kinetic energy E, and the grain experiences a push in the opposite direction. The uncompensated force above is parallel to the rotational axis as the other components of force are averaged out due to grain fast rotation. Applying the characteristic values[7] in Lazarian & Draine (1997), LY02 got the "optimistic" velocity $v \simeq 330(10^{-5}\text{cm}/a)^{1/2}$cm/s for CNM (Fig. 5a) and $v \simeq 370(10^{-5}\text{cm}/a)^{0.7}$cm/s for WNM. The grains tend to be aligned with rotational axes parallel to the magnetic field. Thus grains acquire velocities along the magnetic field lines. It is clear from Fig. 5a that for the chosen set of parameters the effect of H_2 thrust is limited. The percentage of atomic hydrogen is reduced in dark clouds, and the radiation field is weak. Therefore, the velocities driven by the variation of the accommodation coefficient are always much smaller than those due to turbulence so that grains in dark clouds should be fully mixed.

The interstellar medium is turbulent (see Arons & Max 1975; Scalo 1987; Lazarian 1999). Turbulence has been invoked by a number of authors (see Kusaka et al. 1970; Völk et al. 1980; Draine 1985; Ossenkopf 1993; Weidenschilling & Ruzmaikina 1994) to provide substantial grain relative motions.

Grain Motions due to Frictional Drag

In hydrodynamic turbulence, the grain motions are caused by the frictional interaction with the gas. At large scale grains are coupled with the ambient gas, and the slowing fluctuating gas motions mostly cause an overall advection of the grains with the gas (Draine 1985). At small scales grains are decoupled.

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[7]The number of H_2 formation sites is highly uncertain. It may also depend on the interplay of the processes of photodesorption and poisoning (Lazarian 1995b; 1996).

The largest velocity difference occurs on the largest scale where grains are still decoupled. Thus the characteristic velocity of a grain in respect to the gas corresponds to the velocity dispersion of the turbulence on the time scale t_{drag} (Draine & Salpeter 1979). Using the Kolmogorov scaling relation $v_k \propto k^{-1/3}$, Draine (1985) obtained the largest velocity dispersion in hydrodynamic turbulence $v \simeq V(t_{drag}/\tau_{max})^{1/3}$, where τ_{max} is the time scale of the turbulence at the injection scale.

As most interstellar are magnetized and magnetohydrodynamic (MHD) turbulence is much better understood now, a revisit on the problem, namely acceleration by MHD turbulence, is needed. In the following, we shall first introduce some basic idea of MHD turbulence and then give a brief review of our work on dust dynamics in MHD turbulence. MHD perturbations can be decomposed into Alfvénic, slow and fast modes (see Alfvén & Fälthmmar 1963). Alfvénic turbulence is considered by many authors as the default model of interstellar turbulence. Unlike hydrodynamic turbulence, Alfvénic turbulence is anisotropic, with eddies elongated along the magnetic field. This happens because it is easier to mix the magnetic field lines perpendicular to the direction of the magnetic field rather than to bend them. As eddies mix the magnetic field lines at the rate $k_\perp v_k$, where v_k is the mixing velocity at this scale, the magnetic perturbations (waves) propagate along the magnetic field lines at the rate $k_\| V_A$. The Alfvén and slow modes can be described by GS95 model (Goldreich & Sridhar 1995; Cho & Lazarian 2002; Lithwick & Goldreich 2001; see also Cho, Lazarian & Vishniac 2002 for a review). The corner stone of the GS95 model is a critical balance between these rates, i.e., $k_\perp v_k \sim k_\| V_A$, which may be also viewed as coupling of eddies perpendicular to the magnetic field and wave-like motions parallel to the magnetic field. Calculations by Cho & Lazarian (2002; 2003c) demonstrated that fast modes are very similar to acoustic turbulence.

In the MHD case, grain motions are affected by magnetic fields. The charged grains are subjected to the electromagnetic forces which depend on the grain charge. If the periods of Larmor motion τ_L are longer than the gas drag time t_{drag}, the grains do not feel magnetic field directly. Otherwise, grain perpendicular motions are constrained by magnetic field.

As Alfvenic turbulence is anisotropic, it is convenient to consider separately grain motions parallel and perpendicular to the magnetic field. The corresponding discussions can be found in LY02, Lazarian & Yan 2002b.

The velocity dispersion induced by the compressional motion associated with the fast modes also causes the relative movement of the grain to the ambient gas (see YL03). The velocity fluctuations associated with fast modes are always in the direction perpendicular to $\mathbf{B}$ in a low β ($\beta \equiv P_{gas}/P_{mag}$) medium. Thus the grain velocities are also perpendicular to $\mathbf{B}$. In high β medium, grains can have velocity dispersion in any direction as the velocity dispersions of fast modes are radial, i.e., along $\mathbf{k}$.

Acceleration of Grains by Gyroresonance

In YL03 we identified a new mechanism of grain acceleration, namely, gyroresonance that is based on the direct interaction of charged grains with MHD turbulence. There exists an important analogy between dynamics of charged grains and dynamics of cosmic rays (see Yan & Lazarian 2002), and the existing machinery developed for cosmic rays was modified to describe charged

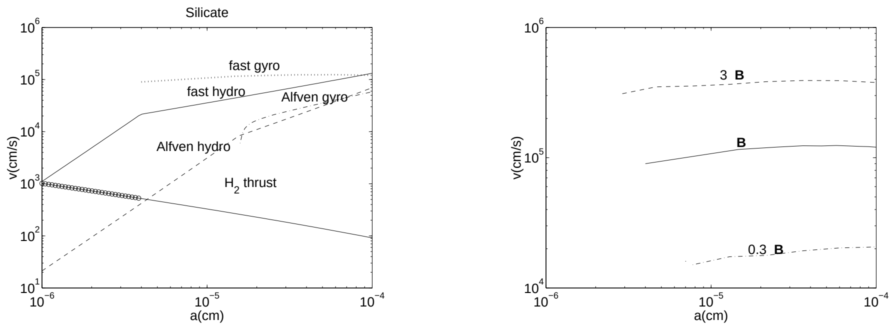

Figure 5. *Left panel*– Relative velocities as a function of radii in CNM for silicate grains. The dotted line represents the gyroresonance with fast modes. The dashdot line refers to the gyroresonance with Alfvén modes. The cutoff is by viscous damping. The dashed line is the result from hydro drag with Alfvén modes (see LY02), the solid line represents the hydro drag with fast modes. Contributions from different mechanisms are approximately additive in squares. The grain velocity driven by H_2 formation (solid line). The part marked by open circles is nonphysical because thermal flipping is not taken into account (YL03). *Right panel*– Grain velocities in CNM gained from gyroresonance for different magnetic field strengths (YLD03).

grain dynamics. The energy exchange involves resonant interactions between the grains and the waves (see YL03). Specifically, the resonance condition is $\omega - k_{\|} v\mu = n\Omega$, ($n = 0, \pm1, \pm2...$), which means that the Doppler-shifted frequency of the wave in the grain's guiding center rest frame $\omega_{gc} = \omega - k_{\|} v\mu$ is a multiple of the particle gyrofrequency Ω. Basically there are two main types of resonant interactions: gyroresonance acceleration and transit acceleration. Transit acceleration ($n = 0$) requires longitudinal motions and only operates with compressible modes. As the dispersion relation is $\omega = kV_f > kV_A$ for fast waves, it is clear that it can be only applicable to super-Alfvenic (for a low β medium) or supersonic (for a high β medium) grains. For low speed grains that we deal with here, gyroresonance is the dominant MHD interaction.

The calculation by YL03 showed grains gain the maximum velocities perpendicular to the magnetic field and therefore the averaged μ decreases. This is understandable since the electric field which accelerates the grain is in the direction perpendicular to the magnetic field.

Then we applied our results to various idealized phases of interstellar medium (YLD03). In Fig. 5a, we show the velocity of grain as a function of grain size in CNM.

The acceleration by gyroresonance in both MC and DC are not so efficient as in other media. This happens because the time for the gyroresonant acceleration t_{drag} are much shorter in MC and DC. In these media, the drag time because of the high density is less than the gyro-period for grains larger than 10^{-5}cm.

It should be noted that the strength of magnetic fields in ISM is still somewhat uncertain and may vary from place to place. We adopted a particular set of values in above calculations. How would the results vary as the magnetic

field strength vary? First of all, we know that the critical condition for acceleration is that the Larmor period τ_L is greater than the period of the turbulent motions at the damping scale. Grains with τ_L less than that can not be accelerated via gyroresonance. Thus the cutoff grain mass m_c varies with the medium, $m_c \sim q\tau_c B/c$. The magnitude of the velocity is a complex function of the magnetic field. For illustration, here we demonstrate the results for 3 times stronger and weaker magnetic field (see Fig. 5b). Since the acceleration via hydro drag by fast modes decreases with the magnetic field, the relative importance of the two processes, namely, gyroresonance and hydro drag depends on the magnitude of the magnetic field. In magnetically dominant region, gyroresonance is dominant. In weakly magnetized region, the decoupled motions provide the highest acceleration rate. The injection scale is another uncertain parameter, but the grain velocity is not so sensitive to it provided that the injection scale is much larger than the damping scale.

6. Discussion

Implications of Rotational Dynamics

Grain Alignment

Grain alignment critically depends on rotational dynamics of grains. Incorporation of thermal fluctuations within theories of grain alignment (Lazarian 1994, 1997ab, Lazarian & Roberge 1997, Lazarian & Draine 1997, Roberge & Lazarian 1999, Weingartner & Draine 2003) introduced substantial changes in our understanding how grains get aligned. Thermal flips (LD99a,b) and thermal trapping (LD99a) that they entail have radically changed some of the contemporary paradigms of grain alignment. Indeed, if grains get thermally trapped as discussed earlier, collisions with gaseous atoms randomize vectors of angular momenta to high degree. Due to efficiency of nuclear relaxation (LD99b) most of the grains do not rotate suprathermally in the absence of radiative torques. This explains why small grains for which radiative torques are not important are only marginally aligned. An alternative explanation of this fact is given by Mathis (1986) and is related to the preferential presence of ferromagnetic inclusions within large grains. However, it is claimed in Lazarian (2003) that data in Whittet et al. (2001) is consistent only with the change of the alignment efficiency with the extinction rather than the grain size. More discussion of grain alignment can be found in the paper by Roberge (2004) in this volume.

Structure of Grains

While grain formation may favor loosely bound conglomerates of low fractal dimension, rapid rotation of grains destroys grain that are not sufficiently compact. The tensile stress calculated in Draine & Lazarian (1998b) did not place severe constrains on small grain considered unless the grains consist of loosely connected parts.

Implications of Translational Motion

Shattering and Coagulation

With the grain relative velocities known, we can make predictions for grain shattering and coagulation. For shattering, we adopt the Jones' et al. (1996) results, namely, the shattering threshold is 2.7km/s for silicate grain and 1.2km/s for carbonaceous grain. The critical sticking velocity were calculated in Chokshi

et al. (1993) (see also Dominik & Tielens 1997).[8] However, experimental work by Blum (2000) shows that the critical velocity is an order of magnitude larger than the theoretical calculation. Comparing these critical velocities with the velocity curve we obtained for various media, we can get the corresponding critical size for each of them (see Table 1). However, given the uncertainties with the parameters as discussed above, we are cautious about these numbers.

ISM	CNM	CNM	WNM	WNM	WIM	WIM
Material	Si	C	Si	C	Si	C
Shattering size (μm)	NA	NA	> 0.2	> 0.2	> 0.003	> 0.001
Coagulation size (μm)	< 0.01	< 0.02	< 0.02	< 0.05	NA	NA

Table 1. The critical shattering and coagulation size in different medium. NA=not applicable.

Correlation between turbulence and grain sizes

Change in the intensity of turbulence should entail variations in grain sizes. The grain velocities are strongly dependent on the maximal velocity of turbulence V at the injection scale, which is highly uncertain. Thus the critical coagulation and shattering sizes would also depend on the amplitude of the turbulence accordingly.

Composition of cosmic ray

It has been shown that the composition of the galactic cosmic ray seems to be better correlated with volatility of elements (Ellison, Drury & Meyer 1997). The more refractory elements are systematically overabundant relative to the more volatile ones. This suggests that the material locked in grains must be accelerated more efficiently than gas-phase ions. This leads to the speculation of acceleration of grain erosion products in shocks (Epstein 1980; Cesarsky & Bibring 1981; Bibring & Cesarsky 1981). If the sputtering happens upstreams, the sputtered products will be carried downstream, where they can be further accelerated to cosmic ray energies with higher efficiencies than gas-phase ions (Epstein 1980). The destruction by shocks may also be a prodigious source of PAHs, HACs and small grains (Jones, Tielens & Hollenbach 1996, Tielens et al. 1994). The stochastic acceleration is more efficient for low speed grains and thus can serve as a preacceleration mechanism for shock acceleration.

Vacuum cleaning and mechanical alignment

Our results indicate that grains can get supersonic through interaction with fast modes. Grains moving supersonically can efficiently vacuum-clean heavy elements as suggested by observations (Wakker & Mathis 2000). The supersonic grains can also be aligned (see a review by Lazarian 2003 and references therein). As pointed out earlier, the scattering is not efficient for slowly moving grains so that we may ignore the effect of scattering to the angular distribution of the grains. Since the acceleration of grains increases with the pitch angle of the grain, the supersonic grain motions will result in grain alignment with long axes perpendicular to the magnetic field.

[8] There are apparent misprints in the numerical coefficient of Eq.(7) in Chokshi et al.(1993) and the power index of Young's modulus in Eq.(28) of Dominik & Tielens (1997).

Grain Segregation and Turbulent Mixing

Our results are also relevant to grain segregation. Grains are the major carrier of heavy elements in the ISM. The issue of grain segregation may have significant influence on the ISM metallicity. Subjected to external forcing, e.g., due to radiation pressure[9], grains gain size-dependent velocities with respect to gas. WD01 have considered the forces on dust grains exposed to anisotropic interstellar radiation fields. They included photoelectric emission, photodesorption as well as radiation pressure, and calculated the drift velocity for grains of different sizes. The velocities they got for silicate grains in the CNM range from 0.1cm/s to 10^3cm/s. Fig. 5a shows that the turbulence produces larger velocity dispersions[10]. Those velocities are preferentially perpendicular to magnetic field, but in many cases the dispersion of velocities parallel[11] to magnetic field will be comparable or greater than the regular velocities above.

More important is that if reconnection is fast (see Lazarian & Vishniac 1999), the mixing of grains over large scales is provided by turbulent diffusivity $\sim VL$. Usually it was assumed that the magnetic fields strongly suppress the diffusion of charged species perpendicular to their directions. However, this assumption is questionable if we notice that motions perpendicular to the local magnetic field are hydrodynamic to high order as suggested by Cho, Lazarian & Vishniac (2002). In fact, recent work by Cho et al. (2003) shows that the diffusion processes in MHD turbulence are as efficient as in hydrodynamic case if the mean magnetic field is weak or moderately strong, i.e., $\mathbf{B_0}$ is $\sim$ equipartition value. This means that from the theoretical perspective, we do expect that grains can be mixed by the MHD turbulence. Therefore we believe that the segregation of very small and large grains speculated in de Oliveira-Costa et al. (2002) is unlikely to happen for typical interstellar conditions.

Interdependence of Rotational and Translational Motions

Coupling of different types of motions is very important for understanding grain dynamics. As we discussed earlier, the coupling of vibrational and rotational motions results in flips that change dynamics of grains.

Similarly translational and rotational motions are interdependent. For instance, frequent flips average out not only uncompensated torques, but also the uncompensated force. As we mentioned earlier, radiative torques can rescue grains from thermal trapping and therefore we show in Fig 5 that grains larger than $\sim 5 \times 10^{-6}$ cm experience uncompensated forces due to H_2 formation.

Fast rotation makes atoms less susceptible to mechanical alignment through gaseous collisions. However, as grains undergo crossovers, they can still be

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[9]Even in the absence of radiation pressure grains can move along magnetic field lines due to the uncompensated forces, e.g. due to an unequal number of active sites of H_2 formation (see P79). Those forces would be mitigated in molecular clouds, which would induce inflow of dust into molecular cloud. The latter would affect metallicity of the newborn stars.

[10]Our calculation show that for the chosen set of parameters the effects of H_2 thrust are also limited.

[11]This dispersion stems from both the fact that the transpositions of matter by fast modes are not exactly perpendicular to magnetic field (see plot in Lazarian & Yan 2002b) and due to randomization of directions of grain velocities by magnetized turbulence (Yan & Lazarian 2003).

aligned via processes that were termed in Lazarian (1995a) crossover and cross sectional alignment (see also Lazarian & Efroimsky 1996; Efroimsky 2002).

Streaming grains get rotation rates that are faster than that of their thermally rotating counterparts. This may allow thermally trapped grain get "untrapped" and therefore acquire suprathermal rotation through uncompensated Purcell's torques (P79). If grains are "helical" in terms of collisions with gaseous atoms the effect of grain spinning up and getting untrapped should be even move pronounced.

In addition, some characteristics of dust grains are affected both by rotational and translational motions. For instance, both fast rotation and collisions limit the structure of grains and prevent very loose aggregates to dominate the extinction.

7. Summary

1. Interstellar grains move relatively to each other and this results in collisions. The outcome of those may be shattering or coagulation depending on the relative velocities of grains. As grains move relatively to gas they adsorb atoms from the gas and this affects dust chemistry. In addition grains get aligned as a result of gas- dust streaming. Grain rotation affects both grain alignment and grain size distribution. Fast rotating grains are not subjected to randomization via gas collisions. Fast rotation destroys loosely connected grains.

2. Grains do not always rotate about their axis of major inertia. Thermal fluctuations cause vibrations of grain angular momentum about the axis of major inertia and occasional flips. The rate of flips depends on the coupling of rotational and vibrational degrees of freedom that is determined by the rate of dissipative processes in the wobbling grain. Frequent flips result in grains being *thermally trapped*, i.e. rotating with thermal velocities in spite of the presence of suprathermal torques.

3. The rate of grain rotation is determined by collisions with neutrals, ions, photons, plasma effects, emission of radiation, nascent H_2 molecules etc. It is also influenced by the grain flipping. Depending on the interplay of these processes, grains can rotate both at a rate that is larger and smaller than the rate of the thermal Brownian motion.

4. Although rotation is classical even for the smallest grains, a number of subtle quantum mechanical effects determine grain dynamics. For instance, plasma drag arising from the interaction of the grain dipole moment with impinging ions is limited by the quantum nature of the interactions. Nuclear internal relaxation is a quantum effect arising from reorienting of spins of nuclei within a wobbling grain. Paradoxically, in terms of coupling of rotational and vibrational degrees of freedom nuclear spins can be much more efficient than their electron counterparts. Resonance paramagnetic relaxation is yet another quantum effect that alleviates alignment of tiny grains.

5. Grains can be accelerated by various mechanisms. Formation of H_2, variations of the accommodation coefficient, photoelectric emission and photodesorption, radiation pressure are the processes that can induce grain motion. However, ubiquitous interstellar turbulence is probably the major driver of relative grain-gas and grain-grain motions. As the turbulence is usually magnetized

and grains are usually charged the magnetic nature of turbulence is essential. Magnetic fields, on one hand, limit the relative gas-grain motions in the direction perpendicular to the local magnetic field. On the other hand, interaction of charged grains with magnetic turbulence results in resonance acceleration of dust. Supersonic grain velocities are attainable as a result of such an interaction.

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